MARS IN THE CURRENT GLACIAL-INTERGLACIAL: GEOLOGICAL EVIDENCE FOR RECENT CLIMATE CHANGE.

J.W. Head[1], J. F. Mustard[1], M.A. Kreslavsky[2], R.E. Milliken[3], D.R. Marchant[4], F. Forget[5], S.C. Schon[1], J.S. Levy[6], [7]M.H. Hecht, [1]J.-B. Madeleine. [1]Brown Univ., Providence RI 02912 (james_head@brown.edu), [2]UCSC, Santa Cruz CA 95064, [3]Univ. Notre Dame, Notre Dame IN 46556, [4]Boston Univ., Boston MA 02215, [5]LMD, CNRS/UPMC/IPSL, Paris, France, [6]Oregon State Univ., Corvallis, OR 97331, [7]JPL, Pasadena, CA 91109.

Introduction: Mars may have experienced the most significant quasi-periodic variations in its climate over the past 10 Myr of any planet in the Solar System [1-3]. Recent improved understanding of the spin axis/orbital history of Mars [1], together with documentation of ancient non-polar ice-related deposits [2], has shown that the last 5 million years, interpreted to represent the most recent glaciation and a current interglacial period [3], are an anomalous period in Mars climate history. Here we assess predictions of the recent glaciation hypothesis [3]. We place this unusual period in the context of longer-term Mars climate history and show that it offers a unique opportunity to explore the deposits and processes that characterize Mars climate variation.

Recent Ice Ages on Mars: Multiple lines of evidence for surface deposits that formed as a result of recent quasi-periodic climate change on Mars 1) span a large range of scales (meters to 100s km), 2) are of diverse nature (morphology [4], topography [5], chemistry [6]), 3) include latitude-dependent features such as gullies [7] and polygons [8] and 4) are remarkably consistent with models of current and past ground ice stability [9]. These data all pointed to the presence of a succession of meters-thick, latitude dependent surface deposits that are a) young, b) ice-rich when formed, and c) whose deposition and removal is driven by climate change that is induced by spin-axis tilting [3]. Latitude is the single variable with which all of these diverse observations correlate and climate is the only process known to be latitude-dependent. All of these factors provide compelling evidence for climate driven water ice and dust mobility and emplacement during the recent period of higher obliquity (Fig. 1).

These observations were interpreted as ice ages [3], during which deposition and removal of mixtures of dust and water ice were controlled by climate variations resulting from quasi-periodic variation in orbital parameters. During periods of higher obliquity (Fig. 1) enhanced polar summer insolation increased atmospheric water vapor and dust content and the surface ice stability zone shifted toward the equator. Rapid transport of water during ~40 kyr higher obliquity periods [10] permitted deposition of several meters of ice and dust. As obliquity decreased, surface ice stability zones shrank toward the polar caps, creating a latitude-dependent sublimation of ice from the uppermost ice mantle, and forming a protective dust lag over the remaining ice. Low obliquity periods (Fig. 1) were too short to remove the mantle completely, and ground ice was stable at high latitudes (>60°) so these areas primarily underwent thermal cycling. In the interglacial period (Fig. 1), obliquity variations damped down, surface ice stability zones migrated to higher latitudes, and the mid-latitude zone then underwent preferential and more prolonged sublimation of ice and desiccation and dissection, causing pitting and erosion of the layered deposits at these latitudes. In summary (Fig. 1), the Mars glacial period was characterized by high obliquity peaks creating warmer polar temperatures (emplacement of the ice-rich mantle), while the interglacial period is characterized by subdued obliquity variations and retreat of the ice stability field to higher latitudes (non-emplacement and removal of mantle). This is in contrast to glacial periods on Earth, which form due to *lower* polar insolation, enhanced snow and ice accumulation, and the spread of continental ice sheets.

The resulting ice age hypothesis [3] is consistent with these previous observations and furthermore is predicted to produce a deposit that: 1) is geologically recent and superposed on underlying terrain, 2) consists of multiple layers, 3) is very ice-rich, 4) varies in character as a function of latitude (undergoing preferential ice loss and layer production at lower latitudes and primarily thermal cycling at higher latitudes), and 5) produces contemporaneous geomorphic features (such as gullies and viscous flow features). Here we investigate several of these predictions and assess exploration opportunities.

1) Presence of Shallow Buried Ice: Diffusion of water vapor into and out of the soil during periods of climate change in response to changing equilibrium conditions is an integral part of any model of climate change [3,9]; the recent ice age model [3], however, predicts actual deposition of snow and ice as meters-thick layers, in contrast to regolith pore ice or secondary ice lenses that might be produced by vapor diffusion alone [11]. Five lines of evidence support extensive deposits of buried ice just below the mantle surface at different latitudes: a) At high latitudes (68°N), the Phoenix Lander exposed nearly pure buried ice a few

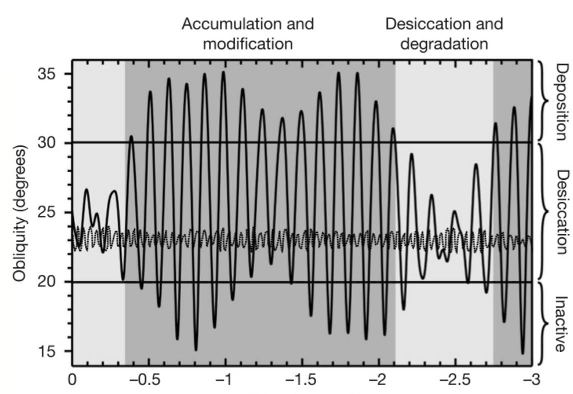

Fig. 1. Orbital forcing of climate in recent Mars history [3]; low amplitude line is Earth obliquity variations.

centimeters below the soil surface beneath the descent engine [12] and in trenches [13]. b) Polygon morphology suggests that polygons at this latitude [14] are "sublimation polygons" [15] indicative of the presence of extensive buried ice. Solar insolation-related polygon asymmetry supports the broader presence of this buried ice [16]. c) At lower latitudes, fresh, post-mantle impact craters have excavated essentially pure buried ice [17]; observations of ejecta and sublimation rates point to very high ice abundances, in excess of pore ice alone. d) Continued analysis of gamma-ray and neutron spectrometer data favor the presence of ice below the soil surface in amounts well in excess of that permitted by pore space alone [18]. e) Extensive buried water ice has been detected in the shallow subsurface (<1 m depth) in southern mid-latitudes [19] on the basis of the observed surface distribution of seasonal CO_2 ice frost on pole-facing slopes, and has been attributed to a perennial ice layer at least 2-3 m thick dating from the last ice age [3]. In summary, evidence of extensive deposits of meters-thick buried ice has been reported at all latitude bands predicted to contain the ice-age mantle deposits [3].

2) Mid-Latitude Layering: The emplacement of ice and dust-rich layers during recent obliquity peaks and their evolution between obliquity maxima were examined theoretically [20] and it was shown that the qualitative prediction [3] (emplacement of ice-dust deposits at high obliquity and concentration of sublimation lags above ice-rich layers to create a stratigraphic sequence) was supported. Do such layers exist? Mid-latitude desiccation and pitting of the mantle during the current interglacial [4] should expose any mantle layering in the pit walls. Examination of HiRISE images in the southern mid-latitudes [21] revealed 168 examples of layering on pole-facing walls of pits, with 3-6 layers observed in each location; layers were a few meters thick, often terraced, and remarkably laterally continuous for many hundreds of meters, offering excellent exposures for further investigation.

3) Additional Morphologic Evidence: The obliquity-peak-dominated ice-age hypothesis (Fig. 1) predicts emplacement of mantles and production of multiple layers at mid-latitudes due to deposition and partial loss by sublimation: a) The discovery of a small very young excess-ejecta crater at 38°N latitude [22] strongly supports the presence of 10-25 m of the mantle in this region prior to its removal, except where armored by the crater ejecta. b) The distribution of "cryokarst" desiccation pits in the mid-latitudes [23] is consistent with the recent interglacial period of ice removal in these zones. c) Cryokarst walls reveal multiple mantle layers [21]. d) A recent comprehensive global mapping of polygon types [14] supports both the ice-rich nature of the substrate in the mantle region and shows latitudinal differences in polygon characteristics.

4) Predicted Behavior at Low Obliquity Extremes: In concert with the high obliquity peaks characteristic of the ice ages are the corresponding low obliquity troughs, when obliquity dips below 20° (Fig. 1). During these periods the CO_2 atmosphere thins considerably [24], condensing onto the surface at high latitudes. The presence of unusual features at high northern latitude interpreted to be CO_2 glacier deposits [25] formed during these low-obliquity periods, and stratigraphically associated with the mantle deposit, supports the formation of the mantle during the ice age.

5) Contemporaneous geomorphic features: Among the latitude dependent geomorphic features correlated with the mantle and ice ages [3] were gullies [7], consisting of an alcove, channel and fan, typically found on pole-facing slopes in the latitude range of 30-42° [26], and thought to involve erosion by fluvial processes [27,28]. Recently, secondary craters have been documented on the wall of an impact crater containing mantling deposits and gully features [29]; the age of the source crater places this gully activity during the ice age (Fig. 1), similar to another gully elsewhere [30]. The stratigraphic relationships of gullies at this site [29] show that melting of the ice-rich mantling deposits is the source of much of the fluvial activity that has carved the gullies [31,32]. More regional treatments of gully distribution and associations [26] support the correlation of melting of the mantle under favorable microenvironment and insolation conditions [33]. In summary, the distribution [26], age [29-30] and characteristics of gullies [26, 31-33] appear to be highly correlated with the formation and evolution of the mantle deposits during the ice age.

Summary and Conclusions: The rich and extensive geological record of the recent ice age and the current interglacial period thus offer unprecedented and accessible opportunities to explore and characterize the individual systematic spin-axis orbital variations (Fig. 1) (e.g., widespread shallowly buried ice, layers, recent fluvial activity) that make up this extreme climate record and to gain insight into the climate processes operating during the more typical periods of the Amazonian history of Mars and the resulting geologic record [2].

References: 1. Laskar et al., *Icarus* 170, 343, 2004; 2. Head and Marchant, *LPSC* 40, 1356, 2009; 3. Head et al., *Nature* 426, 797, 2003; 4. Mustard et al., *Nature* 412, 411, 2001; 5. Kreslavsky and Head, *JGR* 105, 26695, 2000; 6. Boynton et al., *Science* 297, 81, 2002; 7. Malin and Edgett, *JGR* 106, 23429, 2001; 8. Mangold, *Icarus* 174, 336, 2005; 9. Mellon and Jakosky, *JGR* 100, 1995. 10. Mischna et al., *JGR* 108, 5062, 2003; 11. Mellon et al., JGR 114, E00E07, 2009; 12. Smith et al., *Science* 325, 58, 2009; 13. Sizemore et al., *JGR* 115 E00E09, 2010; 14. Levy et al., *JGR* 114, 2009; 15. Marchant et al., *GSAB* 114, 718, 2002; 16. Levy et al, *GRL* 35, 2008; 17. Byrne et al., *Science* 325, 1674, 2009; 18. Chamberlain and Boynton, *JGR* 112, 2007; 19. Vincendon et al., *GRL* 37, L01202, 2010; 20. Shroghofer, *Nature* 449, 192, 2007; 21. Schon et al., *GRL* 36, 2009; 22. Schafer et al., *LPSC* 42; 23. Milliken et al., *JGR* 108, 5057, 2003; 24. Kreslavsky and Head, *GRL* 32, L12202, 2005; 25. Kreslavsky and Head, *LPSC* 41, 1284, 2010; 26. Dickson and Head, *Icarus* 204, 63, 2009; 27. McEwen et al., *Science* 317, 1706, 2007; 28. Head et al, in *Antarctica: Keystone in a Changing World (ISAES)*177, 2007; 29. Schon et al., *Geology* 37, 207, 2009; 30. Reiss et al., *JGR* 109, 2004; 31. Schon and Head, *Icarus* in review, 2010; 32. Schon and Head, *LPSC* 42; 33. Head et al, *PNAS* 105, 13258, 2008.